



US009193958B2

(12) **United States Patent**
Ishige et al.

(10) **Patent No.:** **US 9,193,958 B2**
(45) **Date of Patent:** **Nov. 24, 2015**

(54) **METHOD OF ENZYMATICALLY
SYNTHESIZING 3'-PHOSPHOADENOSINE-5'-
PHOSPHOSULFATE**

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(*) Notice: Subject to any disclaimer, the term of this
patent is extended or adjusted under 35
U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/199,337**

(22) Filed: **Mar. 6, 2014**

(65) **Prior Publication Data**

US 2014/0206042 A1 Jul. 24, 2014

Related U.S. Application Data

(62) Division of application No. 11/814,700, filed as
application No. PCT/JP2006/301062 on Jan. 24, 2006,
now Pat. No. 8,728,789.

(30) **Foreign Application Priority Data**

Jan. 25, 2005	(JP)	2005-016243
May 11, 2005	(JP)	2005-138115
Jul. 26, 2005	(JP)	2005-215663

(51) **Int. Cl.**
C12P 19/32 (2006.01)
C12N 9/12 (2006.01)

(52) **U.S. Cl.**
CPC **C12N 9/1229** (2013.01); **C12N 9/1205**
(2013.01); **C12N 9/1241** (2013.01); **C12P**
19/32 (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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(57) **ABSTRACT**

The invention provides a method for producing 3'-phospho-adenosine 5'-phosphosulfate (PAPS), the method including subjecting ATP to sulfation and phosphorylation by use of adenosine 5'-triphosphate sulfurylase (ATPS) and adenosine 5'-phosphosulfate kinase (APSK), wherein an adenosine 5'-triphosphate (ATP) supply/regeneration system including adenosine 5'-monophosphate (AMP), polyphosphate, polyphosphate-driven nucleoside 5'-diphosphate kinase (PNDK), and polyphosphate:AMP phosphotransferase (PAP), or an adenosine 5'-triphosphate (ATP) supply/regeneration system including adenosine 5'-monophosphate (AMP), polyphosphate, polyphosphate-driven nucleoside 5'-diphosphate kinase (PNDK), and adenylate kinase (ADK) is employed instead of ATP.

5 Claims, 3 Drawing Sheets

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Fig. 1

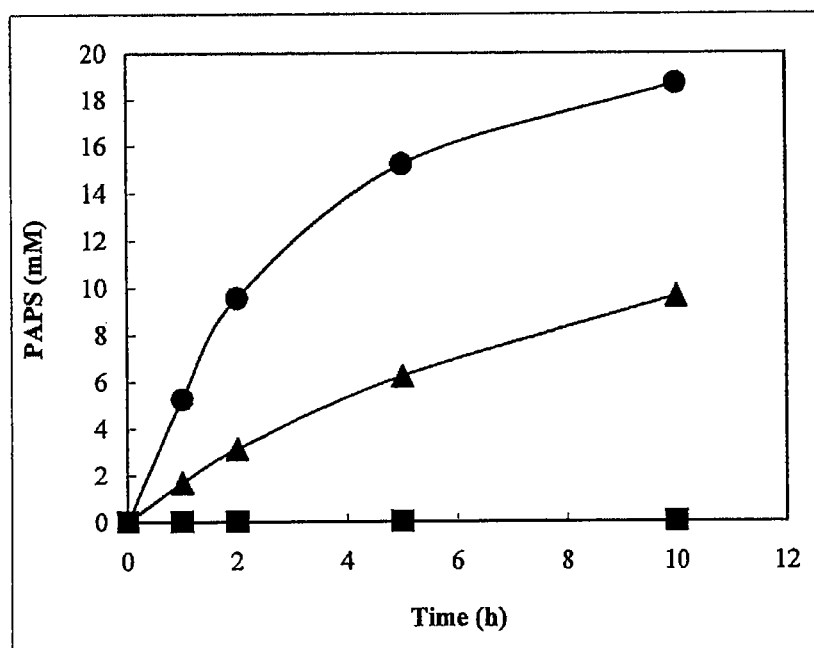


Fig. 2

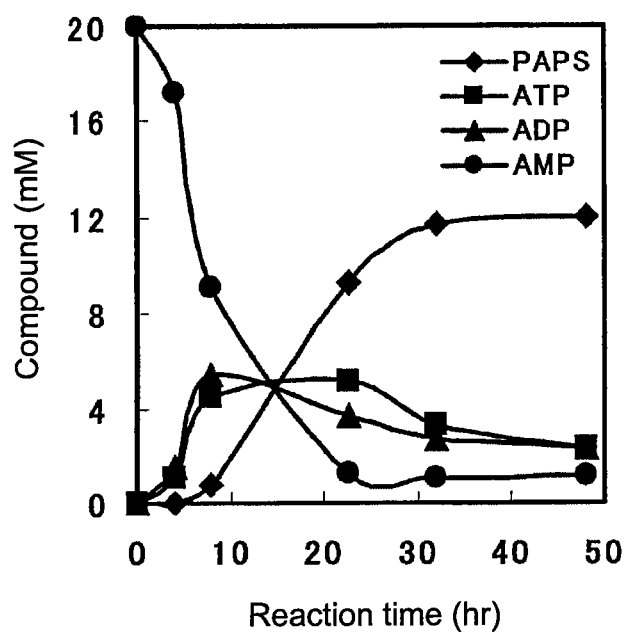


Fig. 3

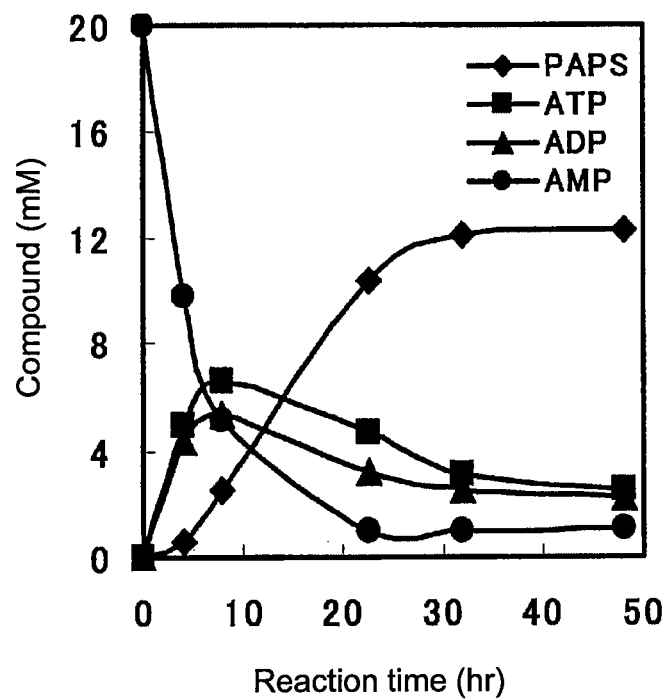


Fig. 4

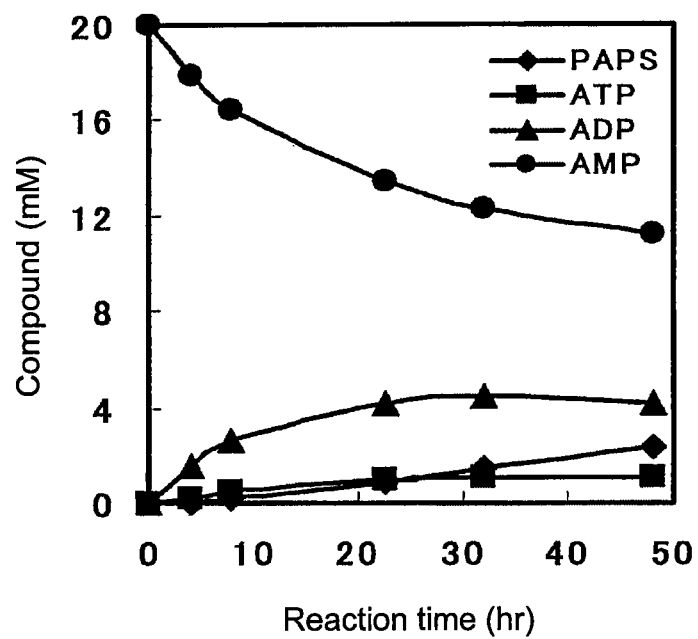
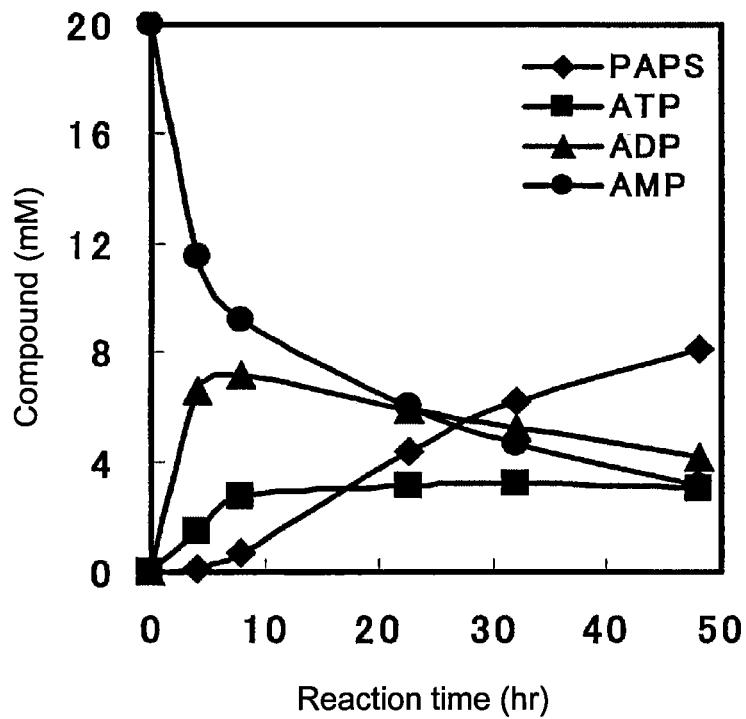


Fig. 5



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METHOD OF ENZYMATICALLY SYNTHESIZING 3'-PHOSPHOADENOSINE-5'-PHOSPHOSULFATE

This application is a divisional of U.S. Ser. No. 11/814,700 filed Jul. 25, 2007, now U.S. Pat. No. 8,728,789, which was a National Stage of PCT/JP06/301062 filed Jan. 24, 2006 and claims the benefit of JP 2005-016243 filed Jan. 25, 2005, JP 2005-138115 filed May 11, 2005, and JP 2005-215663 filed Jul. 26, 2005.

TECHNICAL FIELD

The present invention relates to adenosine 5'-triphosphate sulfurylase (ATPS) derived from *Geobacillus stearothermophilus*, which is a thermotolerant bacterium; to adenosine 5'-phosphosulfate kinase (APSK) derived from *Geobacillus stearothermophilus*; to polyphosphate-driven nucleoside 5'-diphosphate kinase (PNDK) derived from *Pseudomonas aeruginosa*; to an adenosine 5'-triphosphate (ATP) supply/regeneration system employing the PNDK; and to a practical method for enzymatically synthesizing 3'-phosphoadenosine 5'-phosphosulfate (PAPS) through linkage of the ATPS, APSK, and ATP supply/regeneration system.

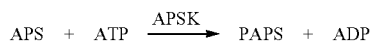
BACKGROUND ART

PAPS is a sulfate donor which is widely employed in living organisms, including microorganisms, plants, and higher animals. PAPS has been reported to be related to several diseases (e.g., proteoglycan-associated diseases). PAPS plays a very important role in vivo, and could be employed in, for example, the field of medicine.

Known methods for enzymatically synthesizing PAPS include a method in which PAPS is produced from ATP through two-step reaction employing two enzymes (ATPS and APSK) extracted from baker's yeast or rat liver (the below-described formulas 1 and 2).

However, this method produces only a small amount (several milligrams to several tens of milligrams) of PAPS, and requires ATP, which is an expensive substance; i.e., this method is not necessarily considered industrially practical.

[F1]



(In the aforementioned formulas, ATP represents adenosine 5'-triphosphate; ADP represents adenosine 5'-diphosphate; APS represents adenosine 5'-phosphosulfate; PPi represents inorganic pyrophosphate; and SO_4^{2-} represents a sulfate ion.)

Therefore, practical production of PAPS requires employment of microorganism-derived enzymes which ensure high productivity and easy handling (first requirement); and establishment of an ATP supply/regeneration system which does not require ATP (i.e., an expensive substance) (second requirement).

In connection with the first requirement, Onda, et al., have reported that PAPS can be efficiently produced through two-step reaction employing two highly thermostable enzymes (ATPS and APSK) derived from a bacterium belonging to the genus *Bacillus* or *Thermus* (Patent Documents 1 to 3).

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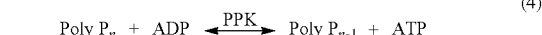
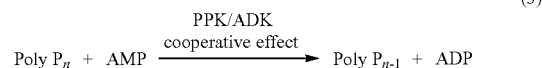
When the method of Onda, et al., is carried out, ATPS and APSK must be purified from a suspension of disrupted thermotolerant bacterium cells. However, the method involves problems in that the amounts of these enzymes contained in the bacterial cells are small, and thus large amounts of the cells must be cultured, and that purification of these enzymes requires a very intricate process.

Meanwhile, in connection with the second requirement, Ibuki, et al., have reported that a method in which a PAPS synthesis system is linked to an ATP regeneration system including acetyl phosphate and acetate kinase, and ADP produced through APSK reaction is converted into ATP for recycling (Non-Patent Document 1).

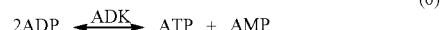
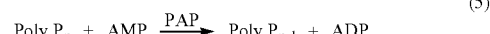
However, this method still employs ATP (i.e., an expensive substance) as a substrate at an early stage of reaction, and employs a large amount of acetyl phosphate (i.e., an expensive substance) as a phosphate donor for ATP regeneration. Therefore, the method has not yet been put into practice.

Conventionally known inexpensive phosphate donors include polyphosphate (Poly P_n). Known ATP supply/regeneration systems employing polyphosphate and adenosine 5'-monophosphate (AMP) include a system represented by the below-described formulas (3) and (4) and utilizing the cooperative effect of polyphosphate kinase (PPK) and adenylylate kinase (ADK) (Patent Document 4); and a system represented by the below-described formulas (5) and (6) and employing polyphosphate:AMP phosphotransferase (PAP) and ADK (Patent Document 5).

[F2]



[F3]



(In the aforementioned formulas, ATP represents adenosine 5'-triphosphate; ADP represents adenosine 5'-diphosphate; AMP represents adenosine 5'-monophosphate; Poly P_n represents polyphosphate; and n represents an integer.)

There has already been reported a method in which the ATP supply/regeneration system utilizing the PPK-ADK cooperative effect is applied to enzymatic synthesis of PAPS (Patent Document 6). However, detailed analysis of this method has revealed that the amount of PAPS produced is at most about 5 mM. Extensive studies on the cause of such low yield have shown that the ATP supply/regeneration system utilizing the PPK-ADK cooperative effect does not function effectively, and difficulty is encountered in maintaining higher concentration of ATP than that of ADP or AMP in the reaction system, resulting in non-efficient PAPS production (see Comparative Example 1 described below).

PPK is considered to function as a polyphosphate synthase in vivo, and the equilibrium of the enzymatic reaction represented by formula (4) is greatly shifted to the side of polyphosphate synthesis (Non-Patent Document 2). As has been indicated, since PPK exhibits low ATP synthesis activity, although the ATP supply/regeneration system employing the

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enzyme functions well in, for example, a reaction in which the concentration of a substrate is low (i.e., about 5 mM or less), the system fails to function satisfactorily in a reaction in which the concentration of a substrate is high (i.e., more than 10 mM).

There has not yet been reported a case where the ATP supply/regeneration system employing PAP and ADK is applied to enzymatic synthesis of PAPS. However, since ADK completely reversibly catalyzes the reaction represented by formula (6), as described below in Comparative Example 2, the concentration of ATP in the reaction system fails to be maintained high, resulting in non-efficient PAPS production.

Therefore, practical production of PAPS requires establishment of a new potent ATP supply/regeneration system which can maintain higher concentration of ATP than that of ADP or AMP.

Examples of means for establishing such a potent ATP supply/regeneration system include employment of *Pseudomonas aeruginosa*-derived polyphosphate-driven nucleoside 5'-diphosphate kinase (PNDK). Recently, *Pseudomonas aeruginosa*-derived PNDK has been identified (Non-Patent Documents 3 and 4), and a gene encoding the enzyme has been obtained (Non-Patent Documents 2 and 5).

Similar to the case of PPK, PNDK exhibits polyphosphate-driven ADP phosphorylation activity. However, the amino acid sequence of PNDK has no homology to that of PPK, and PNDK exhibits remarkably high specific activity; i.e., 100 or more times that of *Escherichia coli*-derived PPK, and about 1,000 times that of *Pseudomonas aeruginosa*-derived PPK (Non-Patent Document 2). In contrast to the case of PPK, PNDK exhibits almost negligibly low polyphosphate synthesis activity, and the reaction equilibrium is greatly shifted to the side of ATP synthesis. Therefore, PNDK is considered an ideal enzyme employed for an ATP supply/regeneration system.

However, productivity of the enzyme PNDK in *Pseudomonas aeruginosa* is low. Therefore, when the enzyme is employed on an industrial scale, a gene for producing the enzyme must be cloned through a genetic recombination technique, and the enzyme must be mass-produced by use of a host such as *Escherichia coli*. However, in experiments previously performed by the present inventors, even when such a genetic recombination technique was employed, productivity of the enzyme is still low, and thus the enzyme was difficult to put into practice.

Patent Document 1: Japanese Patent No. 3098591

Patent Document 2: Japanese Patent No. 3078067

Patent Document 3: Japanese Patent No. 3029915

Patent Document 4: WO 98/48031

Patent Document 5: WO 03/100056

Patent Document 6: JP-A-2002-78498

Non-Patent Document 1: Nucleic Acids Symp. Ser., 27, 171-172 (1992)

Non-Patent Document 2: Proc. Natl. Acad. Sci. USA, 99, 16684-16688 (2002)

Non-Patent Document 3: Proc. Natl. Acad. Sci. USA, 94, 439-442 (1997)

Non-Patent Document 4: Biochem. Biophys. Res. Commun., 281, 821-826 (2001)

Non-Patent Document 5: Proc. Natl. Acad. Sci. USA, 99, 16678-16683 (2002)

DISCLOSURE OF THE INVENTION

Problems to be Solved by the Invention

Therefore, in order to establish a practical PAPS production method, an object of the present invention is to specify

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genes encoding ATPS and APSK in the chromosome of *Geobacillus stearothermophilus* (former *Bacillus stearothermophilus*), which is a thermotolerant bacterium, and to mass-produce the enzymes through a recombinant DNA technique.

Another object of the present invention is to establish efficient production of PNDK through a recombinant DNA technique.

Yet another object of the present invention is to establish a very potent ATP supply/regeneration system employing PNDK, and to provide a method for efficiently producing PAPS through linkage of the ATP supply/regeneration system with ATPS and APSK derived from *Geobacillus stearothermophilus*, which is a thermotolerant bacterium.

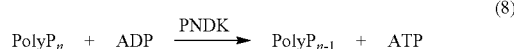
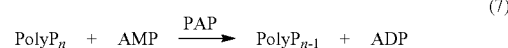
Means for Solving the Problems

In order to achieve the aforementioned objects, the present inventors have conducted extensive studies. As a result, the present inventors have first specified genes encoding ATPS and APSK in the chromosome of *Geobacillus stearothermophilus*, which is a thermotolerant bacterium; and have enabled the enzymes to be mass-produced through a recombinant DNA technique. In addition, the present inventors have considerably enhanced the PAPS synthesis activity of the enzymes by thermally treating an *Escherichia coli* crude extract which produces the enzymes in large amounts, and thus have enabled PAPS to be produced efficiently without subjecting the enzymes to a special purification process.

Subsequently, the present inventors have thoroughly examined a polynucleotide encoding already reported PNDK formed of 357 amino acid residues; and have found that employment of a DNA fragment prepared through artificial deletion of a nucleotide sequence corresponding to several tens of N-terminal amino acid residues considerably enhances productivity of the enzyme without loss of a target enzymatic activity.

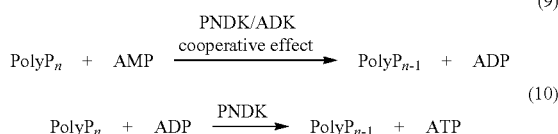
Furthermore, the present inventors have found that when PAP is selected as an enzyme which phosphorylates AMP for production of ADP; the aforementioned PNDK is selected as an enzyme which phosphorylates ADP for production/regeneration of ATP; and these enzymes are employed in combination, ATP can be supplied from AMP in a very efficient manner, and the thus-supplied ATP can be maintained at high concentration (see the below-described formulas 7 and 8).

[F4]



The present inventors have also found that when PNDK is caused to coexist with ADK, similar to the case where PPK coexists with ADK as in Patent Document 4, polyphosphate-driven AMP phosphorylation activity is exhibited through the cooperative effect of PNDK and ADK, and that the thus-produced ADP is immediately converted into ATP through potent ADP phosphorylation activity of PNDK alone, and combination of PNDK and ADK can function as a potent ATP supply/regeneration system wherein ATP is supplied from AMP (see the below-described formulas 9 and 10).

[F5]



The present inventors have also found that when any of the ATP supply/regeneration system including PAP and PNDK and the ATP supply/regeneration system including ADK and PNDK is applied to enzymatic synthesis of PAPS employing ATPS and APSKPAPS derived from *Geobacillus stearothermophilus*, the concentration of ATP in the reaction system can be maintained higher than that of ADP or AMP, resulting in efficient PAPS synthesis.

Accordingly, the present invention provides the following.

- (1) A DNA fragment having a nucleotide sequence of SEQ ID NO: 1, which encodes *Geobacillus stearothermophilus*-derived adenosine 5'-triphosphate sulfurylase (ATPS).
- (2) A DNA fragment having a nucleotide sequence of SEQ ID NO: 1, wherein one to several nucleotides are deleted, substituted, inserted, or added, and which encodes an enzyme exhibiting ATPS activity.
- (3) A DNA fragment which hybridizes with a DNA fragment as recited in (1) above under stringent conditions, and which encodes an enzyme exhibiting ATPS activity.
- (4) A method for preparing ATPS or an enzyme exhibiting ATPS activity, the method comprising preparing a crude enzyme exhibiting ATPS activity through a recombinant DNA technique by use of a DNA fragment as recited in any of (1) to (3) above; and subjecting the thus-prepared crude enzyme to a thermal treatment.
- (5) The preparation method according to (4) above, wherein the thermal treatment is performed at 45 to 65° C.
- (6) A DNA fragment having a nucleotide sequence of SEQ ID NO: 2, which encodes *Geobacillus stearothermophilus*-derived adenosine 5'-phosphosulfate kinase (APSK).
- (7) A DNA fragment having a nucleotide sequence of SEQ ID NO: 2, wherein one to several nucleotides are deleted, substituted, inserted, or added, and which encodes an enzyme exhibiting APSK activity.
- (8) A DNA fragment which hybridizes with a DNA fragment as recited in (6) above under stringent conditions, and which encodes an enzyme exhibiting APSK activity.
- (9) A method for preparing APSK or an enzyme exhibiting APSK activity, the method comprising preparing a crude enzyme exhibiting APSK activity through a recombinant DNA technique by use of a DNA fragment as recited in any of (6) to (8) above; and subjecting the thus-prepared crude enzyme to a thermal treatment.
- (10) The preparation method according to (9) above, wherein the thermal treatment is performed at 45 to 65° C.
- (11) A method for producing 3'-phosphoadenosine 5'-phosphosulfate (PAPS), the method comprising enzymatically synthesizing PAPS from a sulfate ion and adenosine 5'-triphosphate (ATP) by use of ATPS prepared through a method as recited in (4) above and APSK prepared through a method as recited in (9) above.
- (12) A DNA fragment comprising a polynucleotide which is formed of nucleotides 101 to 1,171 in a nucleotide sequence of SEQ ID NO: 9, and which encodes polyphosphate-driven nucleoside 5'-diphosphate kinase (PNDK), wherein a nucleotide sequence corresponding to at least 72 N-terminal amino acid residues is deleted.

(13) The DNA fragment according to (12) above, wherein a nucleotide sequence corresponding to at least 73 amino acid residues is deleted.

(14) The DNA fragment as described in (12) above, wherein a nucleotide sequence corresponding to 72 to 87 amino acid residues is deleted.

(15) The DNA fragment as described in (12) above, wherein a nucleotide sequence corresponding to 73 to 83 amino acid residues is deleted.

(16) The DNA fragment as described in (12) above, wherein a nucleotide sequence corresponding to 73, 77, 80, or 83 amino acid residues is deleted.

(17) A DNA fragment having a nucleotide sequence as recited in any of (12) to (16) above, wherein one to several nucleotides are substituted, inserted, or added, and which encodes an enzyme exhibiting PNDK activity.

(18) A DNA fragment which hybridizes with a DNA fragment as recited in any of (12) to (16) above under stringent conditions, and which encodes an enzyme exhibiting PNDK activity.

(19) A method for producing PNDK, the method comprising preparing PNDK through a recombinant DNA technique by use of a DNA fragment as recited in any of (12) to (18) above.

(20) The PNDK which is prepared through a method as recited in (19) above, and which has an amino acid sequence of SEQ ID NO: 10, wherein at least 72 N-terminal amino acids are deleted.

(21) An adenosine 5'-triphosphate (ATP) supply/regeneration system comprising adenosine 5'-monophosphate (AMP), polyphosphate, polyphosphate-driven nucleoside 5'-diphosphate kinase (PNDK), and polyphosphate:AMP phosphotransferase (PAP).

(22) An adenosine 5'-triphosphate (ATP) supply/regeneration system comprising adenosine 5'-monophosphate (AMP), polyphosphate, polyphosphate-driven nucleoside 5'-diphosphate kinase (PNDK), and adenylate kinase (ADK).

(23) The ATP supply/regeneration system according to (21) or (22) above, wherein the PNDK is derived from a microorganism belonging to the genus *Pseudomonas*.

(24) The ATP supply/regeneration system according to (21) or (22) above, wherein the PNDK is PNDK as recited in (20) above.

(25) The ATP supply/regeneration system according to (21) or (22) above, wherein the PAP is derived from a microorganism belonging to the genus *Acinetobacter*.

(26) The ATP supply/regeneration system according to (21) or (22) above, wherein the ADK is derived from *Escherichia coli* or yeast.

(27) The ATP supply/regeneration system according to (21) or (22) above, which employs, as an enzyme source, a transformant obtained through transformation by a recombinant DNA technique, a treatment product of the transformant, or an enzyme obtained from the treatment product.

(28) A method for producing a useful substance efficiently at low cost through an enzymatic reaction consuming ATP as an energy source and/or a substrate, the method comprising employing an ATP supply/regeneration system as recited in any one of (21) to (26) above as the ATP.

(29) The useful substance production method according to (28) above, wherein the useful substance produced through an enzymatic reaction consuming ATP as an energy source and/or a substrate is 3'-phosphoadenosine 5'-phosphosulfate (PAPS), sugar nucleotide, or S-adenosylmethionine (SAM).

(30) A method for producing 3'-phosphoadenosine 5'-phosphosulfate (PAPS), the method comprising subjecting ATP to sulfation and phosphorylation by use of adenosine 5'-triphosphate sulfurylase (ATPS) and adenosine 5'-phosphosulfate

kinase (APSK), wherein the ATP supply/regeneration system as recited in any one of (21) to (27) above is employed instead of the ATP.

(31) The PAPS production method according to (30) above, wherein the ATPS and the APSK are derived from a micro-organism belonging to the genus *Geobacillus*.

(32) The PAPS production method according to (30) above, which employs ATPS prepared through a method as recited in (4) above, and APSK prepared through a method as recited in (9) above.

(33) The PAPS production method according to (30) above, wherein PAPS is enzymatically synthesized at a reaction temperature of 30 to 50° C.

Effects of the Invention

Under the circumstances where the amino acid sequence and nucleotide sequence of *Geobacillus stearothermophilus*-derived ATPS or APSK have not been reported at all, cloning of genes corresponding to *Geobacillus stearothermophilus*-derived ATPS and APSK, which has been first attained by the present inventors, has enabled *Geobacillus stearothermophilus*-derived ATPS and APSK to be mass-produced through a genetic engineering technique. Meanwhile, although the enzymes produced through a genetic engineering technique exhibit unsatisfactory activity, on the basis of the inventors' finding that thermal treatment (i.e., very simple and practical treatment) of the enzymes exhibit drastically enhanced PAPS synthesis activity, simple and large-scale production of PAPS has now been attained.

Employment of a DNA fragment of already reported PNDK in which a nucleotide sequence corresponding to at least 72 N-terminal amino acid residues is deleted has first realized simple and large-scale production of PNDK having an amino acid sequence in which at least 72 N-terminal amino acid residues are deleted. Since the thus-produced PNDK, in which N-terminal amino acid residues are deleted, maintains PNDK-intrinsic activity, a practical ATP synthesis/regeneration system or GTP synthesis/regeneration system can be established through employment of the PNDK.

When PAPS is synthesized by means of the ATP supply/regeneration system of the present invention, which employs only inexpensive raw materials (e.g., AMP and polyphosphate), the concentration of ATP in the reaction system can be maintained higher than that of ADP or AMP, and PAPS can be synthesized at a Percent conversion with respect to AMP of 60% or more. This synthesis efficiency is five times or more that in the case where PAPS synthesis is performed by means of a conventional ATP supply/regeneration system utilizing the cooperative effect of PPK and ADK, and is 1.5 times or more that in the case where PAPS synthesis is performed by means of an ATP supply/regeneration system employing PAP and ADK.

When there are employed ATPS and APSK derived from a microorganism belonging to the genus *Geobacillus*; PNDK derived from a microorganism belonging to the genus *Pseudomonas*; PAP derived from a microorganism belonging to the genus *Acinetobacter*; and ADK derived from *Escherichia coli* or yeast, even if reaction is performed at 30 to 50° C., PAPS can be efficiently synthesized through cooperation of these enzymes without causing reduction of enzymatic activity.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows change over time in amount of PAPS produced through reactions without employing an ATP supply/

regeneration system (Example 1 (3)) (wherein the symbol "black square" represents the amount of PAPS produced through control reaction; the symbol "black triangle" represents the amount of PAPS produced through reaction employing non-thermally treated crude enzymes; and the symbol "black circle" represents the amount of PAPS produced through reaction employing thermally treated crude enzyme liquids).

FIG. 2 shows change over time in composition in PAPS synthesis reaction employing the ATP supply/regeneration system of the present invention employing ADK and PNDK (Example 3 (7)).

FIG. 3 shows change over time in composition in PAPS synthesis reaction employing the ATP supply/regeneration system of the present invention employing PAP and PNDK (Example 3 (8)).

FIG. 4 shows change over time in composition in PAPS synthesis reaction employing a conventional ATP supply/regeneration system utilizing the cooperative effect of PPK and ADK (Comparative Example 1).

FIG. 5 shows change over time in composition in PAPS synthesis reaction employing a conventional ATP supply/regeneration system utilizing PAP and ADK (Comparative Example 2)

BEST MODES FOR CARRYING OUT THE INVENTION

(A) *Geobacillus stearothermophilus*-Derived ATPS and APSK

Geobacillus stearothermophilus-derived ATPS and APSK corresponds respectively to an enzyme having the amino acid sequence of SEQ ID NO: 3 or 4. Alternatively, *Geobacillus stearothermophilus*-derived ATPS or APSK corresponds respectively to an enzyme having an amino acid sequence of SEQ ID NO: 3 or 4, except that one to several amino acids are deleted, substituted, or added.

As used herein, the expression "deletion of several amino acids" refers to, for example, deletion of 30 or less amino acids (preferably, deletion of 10 or less amino acids). As used herein, the expression "substitution of several amino acids" refers to, for example, substitution of 25 or less amino acids (preferably, substitution of 10 or less amino acids). As used herein, the expression "addition of several amino acids" refers to, for example, addition of 40 or less amino acids (preferably, addition of 20 or less amino acids). Examples of such an amino acid sequence of SEQ ID NO: 3 or 4, except that an amino acid(s) is deleted, substituted, or added, include amino acid sequences having a homology of 85% or more (more preferably 90% or more, particularly preferably 95% or more) to the amino acid sequence of SEQ ID NO: 3 or 4. Even when an enzyme has such a modified amino acid sequence, the enzyme is required to exhibit ATPS or APSK activity.

A gene encoding *Geobacillus stearothermophilus*-derived ATPS or APSK corresponds respectively to a gene having the nucleotide sequence of SEQ ID NO: 1 or 2. Alternatively, a gene encoding *Geobacillus stearothermophilus*-derived ATPS or APSK corresponds respectively to a gene having a nucleotide sequence of SEQ ID NO: 1 or 2, except that one or more nucleotides are deleted, substituted, or added. Examples of such a gene having a nucleotide sequence of SEQ ID NO: 1 or 2, except that one or more nucleotides are deleted, substituted, or added, include a gene which hybridizes a DNA fragment represented by SEQ ID NO: 1 or 2 under stringent conditions. As used herein, the expression "hybridization under stringent conditions" refers to, for example,

hybridization in 0.2×SSC containing 0.1% SDS at 50° C., or hybridization in 1×SSC containing 0.1% SDS at 60° C. Examples of the gene having a nucleotide sequence of SEQ ID NO: 1 or 2, except that one or more nucleotides are deleted, substituted, or added, include a gene having a nucleotide sequence having a homology of 85% or more (more preferably 90% or more, particularly preferably 95% or more) to the nucleotide sequence of SEQ ID NO: 1 or 2. Such a gene can be obtained through, for example, a method in which a target gene is amplified by PCR employing, as primers, synthetic DNA fragments corresponding to both end portions of the nucleotide sequence of SEQ ID NO: 1 or 2, and employing *Geobacillus stearothermophilus* chromosomal DNA as a template.

When the thus-obtained gene is isolated and ligated with vector DNA, the gene can be held in various host-vector systems. There may be employed a variety of hosts, including microorganisms, insect cells, and cultured cells. For example, a microorganism such as *Escherichia coli* EK1 strain or yeast SC1 strain may be employed.

When a microorganism is employed as a host, the vector employed may be any commercially available plasmid so long as it is stably held in the microorganism cells. For example, when *Escherichia coli* is employed as a host, preferably, pTrc99A (Amersham) or a similar plasmid is employed.

When a cloned gene (DNA fragment) is ligated with a downstream region of a specific promoter sequence, ATPS or APSK employed in the present invention can be produced in a large amount. When, for example, pTrc99A, which has an expression-inducible trc promoter, is employed, and isopropyl-β-D-thiogalactopyranoside (IPTG) is added to a culture medium during the course of culturing, ATPS or APSK (i.e., a target product) can be produced.

A transformant can be cultured through a customary method. In the case where, for example, a bacterium belonging to the genus *Bacillus* or *Escherichia* is employed, there may be employed, as a culture medium, a bouillon medium, LB medium (1% trypton, 0.5% yeast extract, 1% sodium chloride), 2×YT medium (1.6% trypton, 1% yeast extract, 0.5% sodium chloride), or a similar medium. Microorganism cells may be collected through the following procedure. Specifically, seed cells are inoculated to such a culture medium, followed by culturing at 30 to 50° C. for about 10 to about 50 hours with optional stirring, and then the thus-cultured cells are separated through centrifugation from the culture broth.

The thus-collected microorganism cells are disrupted through a known technique, such as mechanical disruption (by a Waring blender, a French press, a homogenizer, a mortar, etc.), freeze-thawing, self-digestion, drying (freeze-drying, air-drying, etc.), treatment with an enzyme (e.g., lysozyme), ultrasonic treatment, or chemical treatment (acid treatment, alkali treatment, etc.). The processed cells (e.g., a disrupted product or a cell-wall-denatured or cell-membrane-denatured product of the cells) may be employed as a crude enzyme (ATPS or APSK) liquid in the present invention.

When the aforementioned crude enzyme liquid is subjected to a thermal treatment, the thus-obtained ATPS or APSK exhibits enhanced PAPS synthesis activity. The thermal treatment may be performed, with the temperature being maintained at 45° C. to 65° C. for about five minutes to about one hour. Preferably and effectively, the thermal treatment is performed at 55° C. for about 30 minutes.

(B) *Pseudomonas aeruginosa*-Derived PNDK

The DNA fragment employed in the present invention is a DNA fragment including a polynucleotide which is formed of nucleotides 101 to 1,171 in the nucleotide sequence of SEQ

ID NO: 9, and which encodes PNDK, wherein a nucleotide sequence corresponding to at least 72 N-terminal amino acid residues (preferably 73 amino acid residues) is deleted.

Examples of such a DNA fragment include a DNA fragment wherein a nucleotide sequence corresponding to 72 to 87 amino acid residues is deleted (preferably, a DNA fragment wherein a nucleotide sequence corresponding to 73 to 83 amino acid residues is deleted). More specific examples include a DNA fragment described below in Examples; i.e., a DNA fragment wherein a nucleotide sequence corresponding to 73, 77, 80, or 83 amino acid residues is deleted.

As described below in detail in Examples, such a DNA fragment can be obtained through a method in which a target DNA fragment is amplified by PCR employing two primers (i.e., synthetic DNA corresponding to the 5'-end of a PNDK-encoding ppk2 structural gene in which a nucleotide sequence corresponding to a target amino acid(s) has been deleted, and a synthetic DNA corresponding to the 3'-end of the ppk2 structural gene), and employing *Pseudomonas aeruginosa* chromosomal DNA as a template.

When the thus-obtained DNA fragment is isolated and ligated with vector DNA, various host-vector systems can be established. The PNDK of the present invention (i.e., a target product) can be produced through a generally employed method in a selected host-vector system.

For production of the PNDK of the present invention, there may be employed a variety of hosts, including microorganisms, insect cells, and cultured cells. For example, *Escherichia coli* EK1 strain or yeast SC1 strain may be employed.

When a microorganism is employed as a host, the vector employed may be any commercially available plasmid so long as it is stably held in the microorganism cells. For example, when *Escherichia coli* is employed as a host, preferably, a plasmid such as pTrc99A (Amersham) is employed.

When a cloned gene (DNA fragment) is ligated with a downstream region of a specific promoter sequence, the PNDK of the present invention can be produced in a large amount. When, for example, pTrc99A, which has an expression-inducible trc promoter, is employed, and isopropyl-β-D-thiogalactopyranoside (IPTG) is added to a culture medium during the course of culturing, PNDK (i.e., a target product) can be produced.

A transformant can be cultured through a customary method. In the case where, for example, a bacterium belonging to the genus *Bacillus* or *Escherichia* is employed, there may be employed, as a culture medium, a bouillon medium, LB medium (1% trypton, 0.5% yeast extract, 1% sodium chloride), 2×YT medium (1.6% trypton, 1% yeast extract, 0.5% sodium chloride), or a similar medium. The microorganism cells may be collected through the following procedure. Specifically, seed cells are inoculated to such a culture medium, followed by culturing at 30 to 50° C. for about 10 to about 50 hours with optional stirring, and then the thus-cultured cells are separated through centrifugation from the resultant culture broth.

The thus-collected microorganism cells are disrupted through a known technique, such as mechanical disruption (by a Waring blender, a French press, a homogenizer, a mortar, etc.), freeze-thawing, self-digestion, drying (freeze-drying, air-drying, etc.), treatment with an enzyme (e.g., lysozyme), ultrasonic treatment, or chemical treatment (acid treatment, alkali treatment, etc.). The processed cells (e.g., a disrupted product or a cell-wall-denatured or cell-membrane-denatured product of the cells) may be employed as a crude enzyme (PNDK) liquid in the present invention.

In some cases, there may be employed a partially purified enzyme or purified enzyme prepared by purifying, from the

aforementioned processed cells, a fraction exhibiting PNDK activity through a generally employed enzyme purification technique (e.g., salting-out, isoelectric precipitation, precipitation with an organic solvent, dialysis, or any chromatographic technique).

The thus-prepared PNDK of the present invention corresponds to an employed DNA fragment, and has an amino acid sequence of SEQ ID NO: 10, except that at least 72 N-terminal amino acids are deleted.

(C) ATP Supply/Regeneration System

The ATP supply/regeneration system of the present invention encompasses (i) an ATP supply/regeneration system including AMP, polyphosphate, PNDK, and PAP; and (ii) an ATP supply/regeneration system including AMP, polyphosphate, PNDK, and ADK. As used herein, the ATP supply/regeneration system of the present invention encompasses reagents constituting the ATP supply/regeneration system.

No particular limitation is imposed on the origins of PAP, ADK, and PNDK, all of which are known enzymes, and these enzymes may be derived from, for example, animals, plants, or microorganisms. From the viewpoint of, for example, ease of preparation, preferably, an enzyme derived from a microorganism is employed. Such an enzyme may be prepared through the following procedure: a gene for the enzyme is cloned through a recently developed genetic recombination technique; the thus-cloned gene is produced in a large amount in a host (e.g., *Escherichia coli*); and the enzyme is produced from the resultant recombinant bacterium.

Particularly preferably, there are employed, as enzymes, PNDK derived from the aforementioned microorganism belonging to the genus *Pseudomonas*, PAP derived from a microorganism belonging to the genus *Acinetobacter*, and ADK derived from *Escherichia coli* or yeast.

No particular limitation is imposed on the form of each of the aforementioned enzymes added to the reaction system, so long as the enzyme exhibits a target activity. Specific examples of the form of the enzyme include microorganism cells (including a transformant), a treatment product of the cells, and an enzyme product obtained from the treatment product. Microorganism cells may be collected by culturing the microorganism through a customary method in a culture medium capable of growing the microorganism, followed by collection of cells through centrifugation or a similar technique. Specifically, in the case where, for example, a bacterium belonging to the genus *Bacillus* or *Escherichia* is employed, there may be employed, as a culture medium, a bouillon medium, LB medium (1% trypton, 0.5% yeast extract, 1% sodium chloride), 2xYT medium (1.6% trypton, 1% yeast extract, 0.5% sodium chloride), or a similar medium. Microorganism cells may be collected through the following procedure. Specifically, seed cells are inoculated to such a culture medium, followed by culturing at 30 to 50° C. for about 10 to about 50 hours with optional stirring, and then the thus-cultured cells are separated through centrifugation from the culture broth.

Examples of the processed microorganism cells include a disrupted product or a cell-wall-denatured or cell-membrane-denatured product of cells obtained through treatment of the aforementioned microorganism cells by a generally employed technique, such as mechanical disruption (by a Waring blender, a French press, a homogenizer, a mortar, etc.), freeze-thawing, self-digestion, drying (freeze-drying, air-drying, etc.), treatment with an enzyme (e.g., lysozyme), ultrasonic treatment, or chemical treatment (acid treatment, alkali treatment, etc.).

Examples of the enzyme product include a crude enzyme or purified enzyme prepared by subjecting, to a generally

employed enzyme purification technique (e.g., salting-out, isoelectric precipitation, precipitation with an organic solvent, dialysis, or any chromatographic technique), a fraction exhibiting a target enzymatic activity obtained from the above processed cells.

The concentrations of AMP (commercial product), polyphosphate (commercial product), and enzymes (PAP, PNDK, and ADK) added to the ATP supply/regeneration system of the present invention, which concentrations vary depending on the type of a useful substance to which the ATP supply/regeneration system is applied, can be appropriately determined as follows. Specifically, the concentration of AMP is determined so as to fall within a range of, for example, 1 to 200 mM (preferably 10 to 100 mM); the concentration of polyphosphate is determined so as to fall within a range of 1 to 1,000 mM (preferably 50 to 500 mM) as reduced to inorganic phosphate; and the concentration of each of the enzymes is determined so as to fall within a range of 0.001 units/mL or more (preferably 0.001 to 10 units/mL).

No particular limitation is imposed on the useful substance to which such an ATP supply/regeneration system can be applied, so long as the useful substance is produced through an enzymatic reaction consuming ATP as an energy source and/or a substrate. Specific examples of the useful substance include PAPS, sugar nucleotide, and S-adenosylmethionine (SAM).

(D) Enzymatic Synthesis of PAPS

In PAPS enzymatic synthesis reaction, adenosine 5'-phosphosulfate is produced from ATP and a sulfate ion through sulfation of the 5'-phosphate moiety of ATP by means of ATPS catalytic action (formula 1), and the 3'-hydroxyl moiety of the thus-produced adenosine 5'-phosphosulfate is phosphorylated by use of ATP serving as a phosphate donor by means of APSK catalytic action (formula 2).

[F6]



Commercially available ATP may be added to the reaction system. The ATP concentration employed may be appropriately determined so as to fall within a range of, for example, 1 to 200 mM (preferably 1 to 20 mM). No particular limitation is imposed on the sulfate-group donor added to the reaction system, so long as it generates a sulfate ion in the reaction mixture. The sulfate-group donor employed may be a commercially available sulfate such as sodium sulfate or magnesium sulfate. The concentration of the sulfate-group donor employed may be appropriately determined so as to fall within a range of, for example, 1 to 200 mM (preferably 10 to 100 mM).

PAPS can be synthesized by adding ATP and a sulfate to an appropriate buffer (pH 4 to 9), and adding thereto ATPS in an amount of 0.001 units or more (preferably 0.001 to 1.0 unit) and APSK in an amount of 0.001 units or more (preferably 0.001 to 1.0 unit), followed by allowing reaction to proceed at 20° C. or higher (preferably 30 to 50° C.) for about one to about 50 hours with optional stirring.

ATP may be replaced by any of the aforementioned ATP supply/regeneration systems.

Specifically, PAPS synthesis to which the ATP supply/regeneration system including AMP, polyphosphate, PNDK,

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and PAP is applied can be carried out by adding AMP, a sulfate-group donor, and polyphosphate to an appropriate buffer (pH 4 to 9), and then adding thereto PAP in an amount of 0.001 units/mL or more (preferably 0.001 to 10 units/mL), PNDK in an amount of 0.001 units/mL or more (preferably 0.001 to 10 units/mL or more), ATPS in an amount of 0.001 units or more (preferably 0.001 to 10 units), and APSK in an amount of 0.001 units or more (preferably 0.001 to 10 units), followed by allowing reaction to proceed at 20° C. or higher (preferably 30 to 50° C.) for about one to about 100 hours with optional stirring.

Meanwhile, PAPS synthesis to which the ATP supply/regeneration system including AMP, polyphosphate, PNDK, and ADK is applied can be carried out by adding AMP, a sulfate-group donor, and polyphosphate to an appropriate buffer (pH 4 to 9), and then adding thereto ADK in an amount of 0.001 units/mL or more (preferably 0.001 to 10 units/mL), PNDK in an amount of 0.001 units/mL or more (preferably 0.001 to 10 units/mL or more), ATPS in an amount of 0.001 units or more (preferably 0.001 to 10 units), and APSK in an amount of 0.001 units or more (preferably 0.001 to 10 units), followed by allowing reaction to proceed at 20° C. or higher (preferably 30 to 50° C.) for about one to about 100 hours with optional stirring.

In each of the aforementioned reaction systems, since pyrophosphate produced through ATPS reaction may cause product inhibition, synthesis efficiency can be increased by adding inorganic pyrophosphatase in an amount of 0.001 units/mL or more (preferably 0.001 to 10 units/mL).

After completion of reaction, PAPS produced in the reaction mixture can be isolated and purified through a generally employed chromatography process employing, for example, activated carbon or an ion-exchange resin.

EXAMPLES

The present invention will next be specifically described in detail by way of Examples, which should not be construed as limiting the invention thereto. Throughout the Examples, all procedures, including preparation of DNA, cleavage with restriction enzymes, ligation of DNA by T4 DNA ligase, and transformation of *Escherichia coli*, were performed according to "Molecular Cloning, A Laboratory Manual, Second Edition" (edited by Maniatis, et al., Cold Spring Harbor Laboratory, Cold Spring Harbor, N.Y. (1989)). Nucleotides in reaction mixtures were quantitatively determined through HPLC. Specifically, separation was carried out by use of an ODS-AQ312 column (product of YMC Co.) and a 0.5 M monopotassium phosphate solution as an eluent.

Example 1

(1) Identification of ATPS Gene and APSK Gene

Geobacillus stearothermophilus-derived ATPS gene and APSK gene have not yet been identified, but the nucleotide sequence of a portion of the genomic DNA of 10 strains of the bacterium is disclosed (Accession Number NC_002926). Therefore, it was determined, by means of tBLASTn program, whether or not the disclosed partial sequence of the genomic DNA of the strains contains a DNA region capable of encoding the open reading frame (hereinafter abbreviated as "ORF") of an amino acid sequence similar to that of known *Bacillus subtilis*-derived ATPS (Accession Number CAA04411).

As a result, the chromosome of the strains was found to contain a DNA region capable of encoding the ORF of an

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amino acid sequence similar to that of *Bacillus subtilis*-derived ATPS. In addition, a downstream region of the gene was found to contain a DNA region capable of encoding the ORF of an amino acid sequence similar to that of *Bacillus subtilis*-derived APSK (Accession Number CAA04412). These regions were respectively envisaged as *Geobacillus stearothermophilus*-derived ATPS gene and APSK gene.

Thus, a DNA fragment envisaged as *Geobacillus stearothermophilus*-derived ATPS gene was amplified through PCR as follows. Specifically, by use of the below-described primers (A) and (B), PCR amplification was performed by means of a DNA Thermal Cycler (product of Perkin-Elmer Cetus Instrument) through 30 cycles of treatment, each cycle consisting of the steps of thermal denaturation (94° C., one minute), annealing (55° C., one minute), and polymerization (72° C., two minutes), of a reaction mixture (0.1 mL) containing 50 mM potassium chloride, 10 mM Tris-HCl (pH 8.3), 1.5 mM magnesium chloride, 0.001% gelatin, chromosomal DNA of *Geobacillus stearothermophilus* TH6-2 strain (FERN BP-2758) (0.1 µg), two primer DNAs (0.2 µM each), and ExTaq DNA polymerase (2.5 units). The TH6-2 strain, which is named "*Bacillus stearothermophilus* TH6-2," is deposited as FERN BP-2758 in International Patent Organism Depository, National Institute of Advanced Industrial Science and Technology (Central 6, 1-1-1, Higashi, Tsukuba, Ibaraki, Japan, Postal Code 305-8566; deposited on Feb. 4, 1989). Since *Bacillus stearothermophilus* has been renamed "*Geobacillus stearothermophilus*," for just in case, the TH6-2 strain was deposited as "*Geobacillus stearothermophilus* TH6-2" on Dec. 7, 2005 in the aforementioned International Patent Organism Depository (FERM BP-10466).

(SEQ ID NO: 5)

(A) 5'-TTGAATTCCTTGCCCTCATGAACATGGCAGC-3'

(SEQ ID NO: 6)

(B) 5'-TACTGCAGGCTCATCGCATCCTCCTTTAG-3'

In a manner similar to that described above, a DNA fragment envisaged as *Geobacillus stearothermophilus*-derived APS kinase gene was amplified through PCR by use of the following two primer DNAs (C) and (D):

(SEQ ID NO: 7)

(C) 5'-TTGAATTCGCTAAAGGAGGATCGCGATGA-3'

(SEQ ID NO: 8)

(D) 5'-TTTCGACGACCTTGTCAAATGACCTCCC-3'

After amplification of each of the genes, the reaction mixture was treated with a phenol/chloroform (1:1) mixture. To an aqueous fraction was added ethanol in an amount twice the volume of the aqueous fraction, to thereby precipitate DNA. The collected DNA precipitates were separated through agarose gel electrophoresis according to the method of the literature ("Molecular Cloning, A Laboratory Manual, Second Edition," referred to above), to thereby purify DNA fragments. The DNA was cleaved with restriction enzymes EcoRI and PstI and ligated with plasmid pTrec99A (obtained from Pharmacia Biotech. Co.)—which had been digested with the same restriction enzymes EcoRI and PstI—by use of T4 DNA ligase. *Escherichia coli* JM109 was transformed by use of the resultant ligation mixture, and plasmid pTrec-ynB or pTrec-ynC was isolated from the thus-obtained ampicillin-resistant transformant.

The plasmid pTrec-ynB includes a DNA fragment containing ATPS gene derived from *Geobacillus stearothermophilus*

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TH6-2 strain, and the plasmid pTrc-ynC includes a DNA fragment containing APSK gene derived from the same strain. Analysis of the nucleotide sequences of the thus-cloned genes showed that the *Geobacillus stearothermophilus*-derived ATPS gene has the DNA nucleotide sequence of SEQ ID NO: 1, and the *Geobacillus stearothermophilus*-derived APSK gene has the DNA nucleotide sequence of SEQ ID NO: 2. Translation of these DNA nucleotide sequences into amino acid sequences showed that *Geobacillus stearothermophilus*-derived ATPS has the amino acid sequence of SEQ ID NO: 3, and *Geobacillus stearothermophilus*-derived APSK has the amino acid sequence of SEQ ID NO: 4. The *Geobacillus stearothermophilus*-derived ATPS exhibited 68% amino acid sequence homology with *Bacillus subtilis*-derived ATPS, and the *Geobacillus stearothermophilus*-derived APSK exhibited 63% amino acid sequence homology with *Bacillus subtilis*-derived APSK.

(2) Preparation of Crude Enzyme (ATPS or APSK) Liquid

Escherichia coli JM109 was transformed with pTrc99A vector, pTrc-ynB, or pTrc-ynC, and the resultant transformant was inoculated into a 2×YT culture medium (100 mL) containing 100 µg/mL of ampicillin, followed by shaking culture at 30° C. When the number of cells reached 4×10⁸ cells/mL, IPTG was added to the culture broth so that the final concentration thereof was 0.4 mM, followed by further shaking culture at 30° C. overnight. After completion of shaking culture, the cells were collected through centrifugation (10,000×g, 10 minutes), and then suspended in a buffer (50 mM Tris-HCl (pH 8.0), 0.5 mM EDTA, 1 mM 2-mercaptoethanol) (10 mL). Thereafter, the cells were disrupted through ultrasonic treatment, and the cellular residue was removed through centrifugation (10,000×g, 10 minutes). The thus-obtained supernatant fraction was provided as a crude enzyme liquid.

ATPS activity of each of the thus-prepared crude enzyme liquids was determined as follows. Specifically, pyrophosphatase (Roche Diagnostics) (1 unit/mL), APSK (Calbiochem) (1 unit/mL), and the enzyme liquid were added to a reaction mixture containing Tris-HCl buffer (pH 8) (final concentration: 50 mM), magnesium sulfate (final concentration: 20 mM), and ATP (final concentration: 1 mM), and the resultant mixture was maintained at 37° C. for 10 minutes. Thereafter, reaction was stopped through addition of an ice-cooled 0.5 M sodium dihydrogenphosphate solution. The thus-produced PAPS was quantitatively determined through HPLC, and the amount of ATPS required for production of 1 µmole of PAPS for one minute was defined as one unit (1 U).

Meanwhile, APSK activity of each of the thus-prepared crude enzyme liquids was determined as follows. Specifically, pyrophosphatase (Roche Diagnostics) (1 unit/mL), ATPS (Calbiochem) (1 unit/mL), and the enzyme liquid were added to a reaction mixture containing Tris-HCl buffer (pH 8) (final concentration: 50 mM), magnesium sulfate (final concentration: 20 mM), and ATP (final concentration: 1 mM), and the resultant mixture was maintained at 37° C. for 10 minutes. Thereafter, reaction was stopped through addition of an ice-cooled 0.5 M sodium dihydrogenphosphate solution. The thus-produced PAPS was quantitatively determined through HPLC, and the amount of APSK required for production of 1 µmole of PAPS for one minute was defined as one unit. The results of activity determination are shown in Tables 1 and 2.

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TABLE 1

Strain	ATPS activity (units/mL)	ATPS specific activity (units/mg)
JM109/pTrc99A	<0.1	<0.01
JM109/pTrc-ynB	58	3.4

TABLE 2

Strain	APSK activity (units/mL)	APSK specific activity (units/mg)
JM109/pTrc99A	<0.1	<0.01
JM109/pTrc-ynC	2.5	0.19

(3) Synthesis of PAPS by Use of Crude ATPS Liquid and Crude APSK Liquid

Pyrophosphatase (Roche) (5 units/mL), crude ATPS liquid (0.2 vol. %), and crude APSK liquid (0.5 vol. %) were added to a reaction mixture containing Hepes buffer (pH 8) (final concentration: 50 mM), magnesium chloride (final concentration: 25 mM), sodium sulfate (final concentration: 100 mM), and ATP (final concentration: 50 mM), and the resultant mixture was maintained at 37° C.

Each of crude enzyme liquid was subjected to a thermal treatment; i.e., the crude enzyme liquid was placed in a water bath (temperature: 55° C.) for 30 minutes, and then allowed to stand still at room temperature for 30 minutes, followed by centrifugation, to thereby prepare a supernatant. The thus-prepared supernatant (i.e., thermally treated crude enzyme liquid) was added, in place of the crude enzyme liquid, to the aforementioned reaction mixture in the same amount (by volume) as described above, and the resultant mixture was maintained at the same temperature as described above. For control, in place of the aforementioned crude enzyme liquids, crude enzyme liquids prepared by use of *Escherichia coli* JM109 harboring pTrc99A were added to the aforementioned reaction mixture in the same amounts (by volume) as described above, and the resultant mixture was maintained at the same temperature as described above.

FIG. 1 shows change over time in amount of PAPS produced through each of these reactions. As is clear from FIG. 1, production of PAPS over time is observed in the reactions other than the control reaction, and, in the reaction employing the thermally treated crude ATPS and APSK liquids, PAPS synthesis efficiency is considerably high (i.e., the amount of PAPS produced at different points in time is twice to three times), as compared with the case of the reaction employing the non-thermally treated crude ATPS and APSK liquids. Ten hours after initiation of the reaction employing the thermally treated crude enzyme liquids, ½ ATP conversion was found to be 750. In contrast, ten hours after initiation of the reaction employing the non-thermally treated crude enzyme liquids, ½ ATP conversion was found to be only 38%.

Example 2

(1) Cloning of Gene Encoding PNDK in which N-Terminal Amino Acid Residues are Deleted

Chromosomal DNA of *Pseudomonas aeruginosa* PAO1 strain (ATCC BAA-47) was prepared through the method of Saito and Miura (Biochem. Biophys. Acta., 72, 619 (1963)). Subsequently, 12 primer DNAs shown in Table 3 were syn-

thesized through a customary method, and a gene encoding PNDK in which a different number of N-terminal amino acid residues are deleted was amplified through PCR employing two primer DNAs in any of combinations 1 to 11 shown in Table 4 and employing the aforementioned chromosomal DNA as a template. *Pseudomonas aeruginosa* PAO1 strain is available from ATCC.

TABLE 3

Name	Sequence
PPK2F1	5'-TTCCATGGGAGAGGTGTAAGGCTTTCCT-3' (SEQ ID NO: 11)
PPK2F2	5'-AACCATGGGCGAAGAACCCTGTCAGT-3' (SEQ ID NO: 12)
PPK2F4	5'-AACCATGGCGGTGGCCCTGCAGGTCGCC-3' (SEQ ID NO: 13)
PPK2F5	5'-AACCATGGGCGAGGAGACAGCACCTCG-3' (SEQ ID NO: 14)
PPK2F6	5'-AACCATGGACTATCCCTATCACACGCGG-3' (SEQ ID NO: 15)
PPK2F7	5'-AACCATGGCGCGGATGCGCCGCAACGAG-3' (SEQ ID NO: 16)
PPK2F8	5'-AACCATGGACGAGTACGAGAAGGCCAAG-3' (SEQ ID NO: 17)
PPK2F9	5'-TTCCATGGAGGTGCAGAGCTGGGTGAAG-3' (SEQ ID NO: 18)
PPK2F10	5'-TTCCATGGACAGCACCTCGGCGAGCCT-3' (SEQ ID NO: 19)
PPK2F11	5'-TTCCATGGCGAGCCTGCGGCGAACTAT-3' (SEQ ID NO: 20)
PPK2F13	5'-TTCCATGGTGGCGGCGAACTATCCCTATC-3' (SEQ ID NO: 21)
PPK2R1	5'-TTGGATCCTGCCGTACAAGCAGATCGTG-3' (SEQ ID NO: 22)

TABLE 4

Combination No.	DNA primers	Plasmid
1	PPK2F1 and PPK2R1	pTrc-ppk2
2	PPK2F2 and PPK2R1	pTrc-ppk2N3
3	PPK2F4 and PPK2R1	pTrc-ppk2N60
4	PPK2F5 and PPK2R1	pTrc-ppk2N72
5	PPK2F10 and PPK2R1	pTrc-ppk2N74
6	PPK2F11 and PPK2R1	pTrc-ppk2N78
7	PPK2F13 and PPK2R1	pTrc-ppk2N81
8	PPK2F6 and PPK2R1	pTrc-ppk2N84
9	PPK2F7 and PPK2R1	pTrc-ppk2N89
10	PPK2F8 and PPK2R1	pTrc-ppk2N94
11	PPK2F9 and PPK2R1	pTrc-ppk2N109

PCR amplification of a gene encoding PNDK in which N-terminal amino acid residues are deleted was performed by means of a DNA Thermal Cycler (product of Perkin-Elmer Cetus Instrument) through 30 cycles of treatment, each cycle consisting of the steps of thermal denaturation (94° C., one minute), annealing (55° C., 1.5 minutes), and polymerization (72° C., 1.5 minutes), of a reaction mixture (100 mL) containing 50 mM potassium chloride, 10 mM Tris-HCl (pH 8.3), 1.5 mM magnesium chloride, 0.00115 gelatin, template DNA (0.1 µg), two primer DNAs in any of combinations 1 to 11 shown in Table 4 (0.2 µM each), and ExTaq DNA polymerase (2.5 units).

After amplification of the gene, the reaction mixture was treated with a phenol/chloroform (1:1) mixture. To an aqueous fraction was added ethanol in an amount twice the volume of the aqueous fraction, to thereby precipitate DNA. The collected DNA precipitates were separated through agarose gel electrophoresis according to the method of the literature ("Molecular Cloning, A Laboratory Manual, Second Edition," referred to above), to thereby purify DNA fragments of 0.9 to 1.3 kb. The DNA was cleaved with restriction enzymes

NcoI and BamHI and ligated with plasmid pTrc99A (obtained from Pharmacia Biotech. Co.)—which had been digested with the same restriction enzymes NcoI and BamHI by use of T4 DNA ligase.

Escherichia coli JM109 was transformed by use of the resultant ligation mixture, and plasmid (pTrc-ppk2, pTrc-ppk2N3, pTrc-ppk2N60, pTrc-ppk2N72, pTrc-ppk2N74,

pTrc-ppk2N78, pTrc-ppk2N80, pTrc-ppk2N81, pTrc-ppk2N84, pTrc-ppk2N89, pTrc-ppk2N94, or pTrc-ppk2N109) was isolated from the thus-obtained ampicillin-resistant transformant.

The plasmid pTrc-ppk2 is obtained by inserting, into the NcoI-BamHI cleavage site downstream of the trc promoter of pTrc99A, an NcoI-BamHI DNA fragment containing a gene encoding full-length PNDK. Similarly, the plasmid pTrc-ppk2N3 is obtained by inserting, into the same cleavage site, an NcoI-BamHI DNA fragment containing a gene encoding PNDK in which two N-terminal amino acid residues are deleted (hereinafter referred to as "PNDKN3"); the plasmid pTrc-ppk2N60 is obtained by inserting, into the same cleavage site, an NcoI-BamHI DNA fragment containing a gene encoding PNDK in which 59 N-terminal amino acid residues are deleted (hereinafter referred to as "PNDKN60"); the plasmid pTrc-ppk2N72 is obtained by inserting, into the same cleavage site, an NcoI-BamHI DNA fragment containing a gene encoding PNDK in which 71 N-terminal amino acid residues are deleted (hereinafter referred to as "PNDKN72"); the plasmid pTrc-ppk2N74 is obtained by inserting, into the same cleavage site, an NcoI-BamHI DNA fragment containing a gene encoding PNDK in which 73 N-terminal amino acid residues are deleted (hereinafter referred to as "PNDKN74"); the plasmid pTrc-ppk2N78 is obtained by inserting, into the same cleavage site, an NcoI-BamHI DNA fragment containing a gene encoding PNDK in which 77 N-terminal amino acid residues are deleted (hereinafter referred to as "PNDKN78"); the plasmid pTrc-ppk2N81 is obtained by inserting, into the same cleavage site, an NcoI-BamHI DNA fragment containing a gene encoding PNDK in which 80 N-terminal amino acid residues are deleted (hereinafter referred to as "PNDKN81"); the plasmid pTrc-ppk2N84 is obtained by inserting, into the same cleavage site, an NcoI-BamHI DNA fragment containing a gene encoding

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PNDK in which 83 N-terminal amino acid residues are deleted (hereinafter referred to as "PNDKN84"); the plasmid pTrc-ppk2N89 is obtained by inserting, into the same cleavage site, an NcoI-BamHI DNA fragment containing a gene encoding PNDK in which 88 N-terminal amino acid residues are deleted (hereinafter referred to as "PNDKN89"); the plasmid pTrc-ppk2N94 is obtained by inserting, into the same cleavage site, an NcoI-BamHI DNA fragment containing a gene encoding PNDK in which 93 N-terminal amino acid residues are deleted (hereinafter referred to as "PNDKN94"); and the plasmid pTrc-ppk2N104 is obtained by inserting, into the same cleavage site, an NcoI-BamHI DNA fragment containing a gene encoding PNDK in which 103 N-terminal amino acid residues are deleted (hereinafter referred to as "PNDKN104").

(2) Preparation of Crude Liquid of PNDK which has Undergone Deletion in the N-Terminal Region

Escherichia coli JM109 harboring each of the aforementioned plasmids was inoculated into a 2xYT culture medium (300 mL) containing 100 µg/mL of ampicillin, followed by shaking culture at 37° C. When the number of cells reached 4x10⁸ cells/mL, IPTG was added to the culture broth so that the final concentration thereof was 1 mM, followed by further shaking culture at 37° C. for five hours. After completion of shaking culture, the cells were collected through centrifugation (10,000xg, 10 minutes), and then suspended in a buffer (50 mM Tris-HCl (pH 7.5), 0.5 mM EDTA, 1 mM 2-mercaptoethanol) (30 mL). Thereafter, the cells were disrupted through ultrasonic treatment, and the cellular residue was removed through centrifugation (10,000xg, 10 minutes). The thus-obtained supernatant fraction was provided as a crude enzyme liquid.

(3) Determination of Activity of Crude Liquid of PNDK which has Undergone Deletion in the N-Terminal Region

Unit of PNDK activity of the above-obtained crude enzyme liquid was determined/calculated through the below-described method. Specifically, the crude enzyme liquid was added to 50 mM Tris-HCl buffer (pH 8.0) containing 10 mM magnesium chloride, 80 mM ammonium sulfate, 10 mM ADP, and polyphosphate (30 mM as reduced to inorganic phosphate), and the resultant mixture was maintained at 37° C., to thereby allow reaction to proceed. Reaction was stopped through a thermal treatment at 100° C. for one minute. ATP contained in the reaction mixture was quantitatively determined through high-performance liquid chromatography (HPLC). The activity corresponding to production of 1 µmole of ATP at 37° C. for one minute was defined as one unit. Table 5 shows PNDK activity of the crude liquid of PNDK which has undergone deletion in the N-terminal region.

TABLE 5

Crude enzyme liquid	PNDK activity (units/mL-crude enzyme liquid)
PNDK (control)	7.1
PNDKN3	7.3
PNDKN60	5.2
PNDKN72	8.6
PNDKN74	60.5
PNDKN78	84.3
PNDKN81	29.2

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TABLE 5-continued

Crude enzyme liquid	PNDK activity (units/mL-crude enzyme liquid)
PNDKN84	191
PNDKN89	4.9
PNDKN94	3.8
PNDKN109	1.2

A particularly large difference in specific activity between the PNDKs is not observed. Therefore, as is clear from Table 5, employment of a DNA fragment in which a nucleotide sequence corresponding to 73 to 83 amino acid residues is deleted enables PNDK to be prepared in a large amount.

Example 3

(1) Preparation of PNDK

Pseudomonas aeruginosa-derived PNDK was prepared as described in Example 2.

(2) Preparation of PPK

Escherichia coli PPK was prepared through the method described in the literature (J. Biosci. Bioeng., 91, 557-563 (2001)).

Unit of PPK activity was calculated through the below-described method. Specifically, an enzyme sample liquid was added to 50 mM Tris-HCl buffer (pH 8.0) containing 10 mM magnesium chloride, 80 mM ammonium sulfate, 10 mM ADP, and polyphosphate (30 mM as reduced to inorganic phosphate), and the resultant mixture was maintained at 37° C. for 10 minutes. Thereafter, reaction was stopped through treatment of the mixture in a boiling water bath for one minute. ATP contained in the reaction mixture was quantitatively determined through high-performance liquid chromatography (HPLC). The activity corresponding to production of 1 µmole of ATP for one minute was defined as one unit.

(3) Preparation of PAP

Acinetobacter johnsonii-derived PAP was prepared through the method described in the literature (WO 03/100056).

Unit of PAP activity was calculated through the below-described method. Specifically, an enzyme sample liquid was added to 50 mM Tris-HCl buffer (pH 8.0) containing 10 mM magnesium chloride, 80 mM ammonium sulfate, 10 mM AMP, and polyphosphate (30 mM as reduced to inorganic phosphate), and the resultant mixture was maintained at 37° C. for 10 minutes. Thereafter, reaction was stopped through treatment of the mixture in a boiling water bath for one minute. ATP contained in the reaction mixture was quantitatively determined through high-performance liquid chromatography (HPLC). The activity corresponding to production of 1 µmole of ADP for one minute was defined as one unit.

(4) Preparation of ADK

Escherichia coli ADK was prepared through the method described in the literature (Proc. Natl. Acad. Sci. USA, 97, 14168-14171 (2000)).

Unit of ADK activity was calculated through the below-described method. Specifically, an enzyme sample liquid was added to 50 mM Tris-HCl buffer (pH 8.0) containing 10 mM magnesium chloride, 10 mM AMP, and 10 mM ATP, and the

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resultant mixture was maintained at 37° C. for 10 minutes. Thereafter, reaction was stopped through treatment of the mixture in a boiling water bath for one minute. ATP contained in the reaction mixture was quantitatively determined through high-performance liquid chromatography (HPLC). The activity corresponding to production of 2 μmole of ADP for one minute was defined as one unit.

(5) Preparation of Inorganic Pyrophosphatase

Inorganic pyrophosphatase manufactured by Roche Diagnostics was employed.

Unit of inorganic pyrophosphatase activity was calculated through the below-described method. Specifically, an enzyme sample liquid was added to 50 mM Tris-HCl buffer (pH 8.0) containing 10 mM magnesium chloride and 10 mM inorganic pyrophosphate, and the resultant mixture was maintained at 37° C. for 10 minutes. Thereafter, reaction was stopped through treatment of the mixture in a boiling water bath for one minute. The thus-produced inorganic phosphate was quantitatively determined through the molybdenum blue method ("Treatise on Analytical Chemistry," edited by I. M. Kolthoff & P. J. Elving, Vol. 5, pp. 317-402, Interscience, New York (1961)). The amount of inorganic pyrophosphatase required for production of 2 μmole of inorganic phosphate for one minute was defined as one unit.

(6) Preparation of ATPS and APSK

Geobacillus stearothermophilus-derived ATPS and APSK were prepared as described in Example 1.

(7) PAPS Synthesis Employing the ATP Supply/Regeneration System of the Present Invention Employing ADK and PNDK

ADK (0.1 units/mL), PNDK (0.1 units/mL), ATPS (0.25 units/mL), APSK (0.25 units/mL), and inorganic pyrophosphatase (1.0 unit/mL) were added to 50 mM Hepes-KOH buffer (pH 8.0) containing 25 mM magnesium chloride, 20 mM AMP, 100 mM sodium sulfate, and polyphosphate (100 mM as reduced to phosphate), and the resultant mixture was maintained at 37° C. FIG. 2 shows change over time in composition of the reaction mixture. The concentration of produced ATP was maintained higher than that of ADP or AMP during reaction, and the amount of PAPS produced through 48-hour reaction was found to be 12.0 mM (Percent conversion with respect to AMP: 60%).

(8) PAPS Synthesis Employing the ATP Supply/Regeneration System of the Present Invention Employing PAP and PNDK

PAP (0.1 units/mL), PNDK (0.1 units/mL), ATPS (0.25 units/mL), APSK (0.25 units/mL), and inorganic pyrophosphatase (1.0 unit/mL) were added to 50 mM Hepes-KOH buffer (pH 8.0) containing 25 mM magnesium chloride, 20 mM AMP, 100 mM sodium sulfate, and polyphosphate (100 mM as reduced to phosphate), and the resultant mixture was maintained at 37° C. FIG. 3 shows change over time in composition of the reaction mixture. The concentration of produced ATP was maintained higher than that of ADP or AMP during reaction, and the amount of PAPS produced through

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48-hour reaction was found to be 12.3 mM (Percent conversion with respect to AMP: 62%).

(9) PAPS Synthesis Employing the ATP Supply/Regeneration System of the Present Invention Employing PAP and PNDK (Large-Scale Production)

An aqueous solution (1 L) containing 25 mM magnesium chloride, 40 mM AMP, 100 mM sodium sulfate, and polyphosphate (100 mM as reduced to phosphate) was prepared in a thermostatic reaction bath (capacity: 2 L), and the pH of the solution was adjusted to 8.0 with sodium hydroxide. Thereafter, the solution was maintained at 37° C., and then PAP (500 units), PNDK (500 units), ATPS (250 units), APSK (250 units), and inorganic pyrophosphatase (10,000 units) were added to the solution, to thereby initiate reaction. Six hours after initiation of reaction, polyphosphate (100 mM as reduced to phosphate) was further added to the reaction mixture. During reaction, the pH of the reaction mixture was maintained at 8.0 with sodium hydroxide. As a result, the amount of PAPS produced through 30-hour reaction reached 29.3 mM (Percent conversion with respect to AMP: 730%).

Comparative Example 1

PAPS Synthesis Employing Conventional ATP Supply/Regeneration System Utilizing the Cooperative effect of PPK and ADK

PPK (0.1 units/mL), ADK (0.1 units/mL), ATPS (0.25 units/mL), APSK (0.25 units/mL), and inorganic pyrophosphatase (1.0 unit/mL) were added to 50 mM Hepes-KOH buffer (pH 8.0) containing 25 mM magnesium chloride, 20 mM AMP, 100 mM sodium sulfate, and polyphosphate (100 mM as reduced to phosphate), and the resultant mixture was maintained at 37° C. FIG. 4 shows change over time in composition of the reaction mixture. The concentration of produced ATP was maintained lower than that of ADP or AMP during reaction, and the amount of PAPS produced through 48-hour reaction was found to be only 2.3 mM (Percent conversion with respect to AMP: 12%).

Comparative Example 2

PAPS Synthesis Employing Conventional ATP Supply/Regeneration System Utilizing PAP and ADK

PAP (0.1 units/mL), ADK (0.1 units/mL), ATPS (0.25 units/mL), APSK (0.25 units/mL), and inorganic pyrophosphatase (1.0 unit/mL) were added to 50 mM Hepes-KOH buffer (pH 8.0) containing 25 mM magnesium chloride, 20 mM AMP, 100 mM sodium sulfate, and polyphosphate (100 mM as reduced to phosphate), and the resultant mixture was maintained at 37° C. FIG. 5 shows change over time in composition of the reaction mixture. The concentration of produced ATP was maintained lower than that of ADP or AMP during reaction, and the amount of PAPS produced through 48-hour reaction was found to be as small as 8.2 mM (Percent conversion with respect to AMP: 41%).

SEQUENCE LISTING

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<211> LENGTH: 1167

<212> TYPE: DNA

<213> ORGANISM: *Geobacillus stearothermophilus*

<400> SEQUENCE: 1

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gagctgatcg gaacggggcgc ctacagcccc ctactgggtt ttttaacgaa aacggattac      180
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taccatgtcg tcctttccgg caccgaaagt cgtgaaatgc tgcgcaacgg ccaagtgcgg     1080
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gtggccaatg ccgtctccag acgactgttt gagctcggca ttcagaatta tgtcttagac      180
ggcgacaaca tccggcacgg gctcaataaa gatctcggct tttccgccgc cgaccggacg      240
gaaaaacatc gccgcacggc cgaagtggca aagctgtttg tcgacagcgg ccagtgtgtg      300
ctgacggcgt tcactcgcgc gtttgcgaa gaccgggcgc tcgtccgccg cttagtcgaa      360
gaagacgagt ttatcgaat ttacgtcaac tgcccgtttg aagaatgcga aaagcgcgat      420
ccgaaagggc tgtatcaaaa agctcgcgcg ggggaaatcc gtgaatttac gggcatcgac      480
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35          40          45
Ser Pro Leu Thr Gly Phe Leu Thr Lys Thr Asp Tyr Asp Ala Val Val
50          55          60
Glu Thr Met Arg Leu Ser Asp Gly Thr Val Trp Ser Ile Pro Ile Thr
65          70          75          80
Leu Ala Val Thr Glu Glu Lys Ala Lys Glu Leu Ala Val Gly Asp Lys
85          90          95
Ala Lys Leu Val Tyr Arg Gly Asp Val Tyr Gly Val Ile Glu Ile Ala
100         105         110
Asp Ile Tyr Arg Pro Asp Lys Thr Lys Glu Ala Lys Leu Val Tyr Lys
115        120        125
Thr Asp Glu Leu Ala His Pro Gly Val Arg Lys Leu Phe Glu Lys Pro
130        135        140
Asp Val Tyr Val Gly Gly Glu Ile Thr Leu Val Lys Arg Thr Asp Lys
145        150        155        160
Gly Gln Phe Ala Ala Phe Tyr Phe Asp Pro Ala Glu Thr Arg Lys Lys
165        170        175
Phe Ala Glu Phe Gly Trp Asn Thr Val Val Gly Phe Gln Thr Arg Asn
180        185        190
Pro Val His Arg Ala His Glu Tyr Ile Gln Lys Cys Ala Leu Glu Ile
195        200        205
Val Asp Gly Leu Phe Leu Asn Pro Leu Val Gly Glu Thr Lys Ala Asp
210        215        220
Asp Ile Pro Ala Asp Ile Arg Met Glu Ser Tyr Gln Val Leu Leu Glu
225        230        235        240
Asn Tyr Tyr Pro Lys Asp Arg Val Phe Leu Gly Val Phe Gln Ala Ala
245        250        255
Met Arg Tyr Ala Gly Pro Arg Glu Ala Ile Phe His Ala Met Val Arg
260        265        270
Lys Asn Phe Gly Cys Thr His Phe Ile Val Gly Arg Asp His Ala Gly
275        280        285
Val Gly Asn Tyr Tyr Gly Thr Tyr Asp Ala Gln Lys Ile Phe Leu Asn
290        295        300
Phe Thr Ala Glu Glu Leu Gly Ile Thr Pro Leu Phe Phe Glu His Ser
305        310        315        320
Phe Tyr Cys Thr Lys Cys Glu Gly Met Ala Ser Thr Lys Thr Cys Pro
325        330        335
His Asp Ala Lys Tyr His Val Val Leu Ser Gly Thr Lys Val Arg Glu
340        345        350
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<213> ORGANISM: Artificial Sequence
<220> FEATURE:
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<220> FEATURE:
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cagtcccccc tccccgagc aaccgcgcgc gcagccggcc aagccggccc ggccagccgc      180
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35      40      45
Arg Glu Glu Ile Gln Ala Ile Ser Gln Lys Pro Val Ala Leu Gln Val
50      55      60
Ala Ser Ala Pro His Gly Ser Ser Glu Asp Ser Thr Ser Ala Ser Leu
65      70      75      80
Pro Ala Asn Tyr Pro Tyr His Thr Arg Met Arg Arg Asn Glu Tyr Glu
85      90      95
Lys Ala Lys His Asp Leu Gln Ile Glu Leu Leu Lys Val Gln Ser Trp
100     105     110
Val Lys Glu Thr Gly Gln Arg Val Val Val Leu Phe Glu Gly Arg Asp
115     120     125
Ala Ala Gly Lys Gly Gly Thr Ile Lys Arg Phe Met Glu His Leu Asn
130     135     140
Pro Arg Gly Ala Arg Ile Val Ala Leu Glu Lys Pro Ser Ser Gln Glu
145     150     155     160
Gln Gly Gln Trp Tyr Phe Gln Arg Tyr Ile Gln His Leu Pro Thr Ala
165     170     175
Gly Glu Met Val Phe Phe Asp Arg Ser Trp Tyr Asn Arg Ala Gly Val
180     185     190
Glu Arg Val Met Gly Phe Cys Ser Pro Leu Gln Tyr Leu Glu Phe Met
195     200     205
Arg Gln Ala Pro Glu Leu Glu Arg Met Leu Thr Asn Ser Gly Ile Leu
210     215     220
Leu Phe Lys Tyr Trp Phe Ser Val Ser Arg Glu Glu Gln Leu Arg Arg
225     230     235     240
Phe Ile Ser Arg Arg Asp Asp Pro Leu Lys His Trp Lys Leu Ser Pro
245     250     255
Ile Asp Ile Lys Ser Leu Asp Lys Trp Asp Asp Tyr Thr Ala Ala Lys
260     265     270
Gln Ala Met Phe Phe His Thr Asp Thr Ala Asp Ala Pro Trp Thr Val
275     280     285
Ile Lys Ser Asp Asp Lys Lys Arg Ala Arg Leu Asn Cys Ile Arg His
290     295     300
Phe Leu His Ser Leu Asp Tyr Pro Asp Lys Asp Arg Arg Ile Ala His
305     310     315     320
Glu Pro Asp Pro Leu Leu Val Gly Pro Ala Ser Arg Val Ile Glu Glu
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<223> OTHER INFORMATION: Description of Artificial Sequence: Synthetic primer

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<220> FEATURE:

<223> OTHER INFORMATION: Description of Artificial Sequence: Synthetic primer

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<213> ORGANISM: Artificial Sequence

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<223> OTHER INFORMATION: Description of Artificial Sequence: Synthetic primer

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<400> SEQUENCE: 15

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28

<210> SEQ ID NO 16

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<213> ORGANISM: Artificial Sequence

<220> FEATURE:

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28

The invention claimed is:

1. A method for producing a substance by an enzymatic reaction that uses ATP as an energy source and/or a substrate, the method comprising:

providing components of an enzymatic reaction and an ATP supply/regeneration system, wherein the ATP supply/regeneration system produces ATP, and

performing the enzymatic reaction in the presence of the ATP supply/regeneration system to produce the substance, wherein the ATP supply/regeneration system comprises adenosine 5'-monophosphate (AMP), polyphosphate: AMP phosphotransferase (PAP), polyphosphate, and a polyphosphate-driven nucleoside 5'-diphosphate kinase (PNDK) that consists of the amino acid sequence of

amino acids 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, or 87 to 357 of SEQ ID NO:10 and PNDK activity.

2. The method of claim 1, wherein the substance is 3'-phosphoadenosine 5'-phosphosulfate (PAPS), a sugar nucleotide, or S-adenosylmethionine (SAM). 5

3. A method for producing 3'-phosphoadenosine 5'-phosphosulfate (PAPS), the method comprising:

providing adenosine 5'-triphosphate sulfurylase (ATPS), adenosine 5'-phosphosulfate kinase (APSK), and an ATP supply/regeneration system, wherein the ATP supply/regeneration system produces ATP, and 10

allowing ATPS and APSK to sulfate and phosphorylate the ATP to produce PAPS,

wherein the ATP supply/regeneration system comprises adenosine 5'-monophosphate (AMP), polyphosphate: AMP phosphotransferase (PAP), polyphosphate, and a polyphosphate-driven nucleoside 5'-diphosphate kinase (PNDK) that consists of the amino acid sequence of amino acids 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, or 87 to 357 of SEQ ID NO:10 and has PNDK activity. 15 20

4. The method of claim 3, wherein the ATPS and the APSK are from a microorganism belonging to the genus *Geobacillus*. 25

5. The method of claim 3, wherein the PAPS is produced at a temperature of 30 to 50° C.

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